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Tuning Performance of Silicon Carbide Micro-resonators

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Abstract Silicon carbide microresonators have been designed, fabricated and tested. Three designs have been studied: cantilever, bridge and ring resonators. The devices have been actuated electrothermally and sensed piezoelectrically. The resonant frequency as well as the amount of frequency shift as a function of DC bias voltage for the three designs have been characterized electrically using two-port measurements. It has been found that the DC tuning sensitivities of the ring and bridge resonators (between 58,000 ppm/V and 62,000 ppm/V) are significantly higher than for the cantilever (240 ppm/V). Simulations have shown that a larger temperature change, hence a larger compressive stress induced in the SiC layer exists in the bridge design compared to the cantilever design as the DC bias voltage is increased. The higher DC tuning sensitivity for the bridge design could be a result of the combination of the location of the electrode thus causing higher thermally induced compressive stress as well as the clamped-clamped beam configuration.

Introduction

Silicon carbide (SiC) has shown great potential for use as a structural material for microelectromechanical systems (MEMS) resonators. MEMS resonators are utilized in applications such as timing oscillators, filters, accelerometers and gyroscopes. The properties of SiC include chemical inertness, robustness and resistance to radiation [1, 2], which are advantageous when implementing MEMS resonators for harsh environment applications or where reliability of devices is of importance.

Electrothermal excitation of MEMS resonators has been demonstrated previously [3, 4] and offers advantages over the electrostatic method of actuation, which requires more complex fabrication steps, higher bias and actuation voltages. In addition, it has been demonstrated that by varying the DC bias voltage applied to the actuation electrodes, the resonant frequency of the device structures can be tuned [5], a behavior that can be exploited to correct for environmentally-induced frequency drift [6]. For the electrical read-out of the mechanical vibrations of a resonator, piezoelectric transduction is preferred to electrostatic, due to its higher electromechanical coupling [7] and the ability to provide an output signal without the need for an external bias.

Piezoelectric read-out of electrothermally actuated SiC MEMS resonators has been demonstrated previously using devices of various designs including cantilevers [8], bridges [9, 10] and rings [11]. The design is critical in determining resonator performance, with the size of the structure determining the resonant frequency and the electrode design influencing the mechanical vibration amplitude [12].

In this paper, the tuning performance of three different designs of SiC resonators will be compared. All the devices have been actuated electrothermally and sensed piezoelectrically. The design and fabrication of cantilever, bridge and ring resonators will be reported. The DC bias tuning performance of the three designs has been characterized using two-port measurements of the frequency response.

Finite element method (FEM) simulations have been performed, using *CoventorWare*, to investigate the influence of the temperature and stress on the resonant frequency shift.

Actuation and Sensing Principles

Electrothermal Actuation

A SiC resonator can be driven into resonance electrothermally by applying an input signal across metal electrodes that are positioned on top. Joule heating is generated by the voltage drop across the electrode, which heats the bimorph metal/SiC structure. The two materials have different thermal coefficients of expansion (TCE), which will result in mechanical strain as the entire bilayer structure heats up. The power dissipated in the electrode is proportional to the square of the actuation voltage, as explained in detail elsewhere [5]. If the actuation voltage has a DC and AC component, the resonator will be driven into resonance when the frequency of the actuation voltage is equal to the mechanical resonant frequency, f_0 .

Piezoelectric Sensing

In order to sense the mechanical vibrations of a SiC resonator electrically, a layer of piezoelectric material is positioned on top. When the piezoelectric material, such as lead zirconate titanate (PZT), is subjected to a mechanical strain, an electric potential is produced across material stack. A vibrating structure will induce alternating mechanical strain in the piezoelectric layer, which will result in an alternating output voltage that can be measured. Therefore, the vibration amplitude and frequency of vibration of the resonator can be deduced.

Fabrication and Measurements

A side-view schematic of a SiC resonator that can be actuated electrothermally and sensed piezoelectrically is shown in Fig. 1. The fabrication process has been explained in detail elsewhere [8] and is summarized below. Starting with a 2 μm layer of cubic SiC (3C-SiC) on silicon substrate provided by NOVASiC, a 500 nm silicon dioxide (SiO_2) passivation layer has been grown thermally before the deposition of a stack of alternating layers of platinum (Pt) and PZT. The single layer Pt and multi-layer Pt/PZT/Pt have been patterned photolithographically and etched to create an input electrothermal electrode and an output piezoelectric port, respectively. Finally, a SiO_2 masking layer has been deposited, patterned and etched into the shape of either a cantilever, bridge or ring before inductively coupled plasma (ICP) has been used to etch the 3C-SiC layer. XeF_2 vapor has been used to etch the Si substrate to complete the release of the resonators.

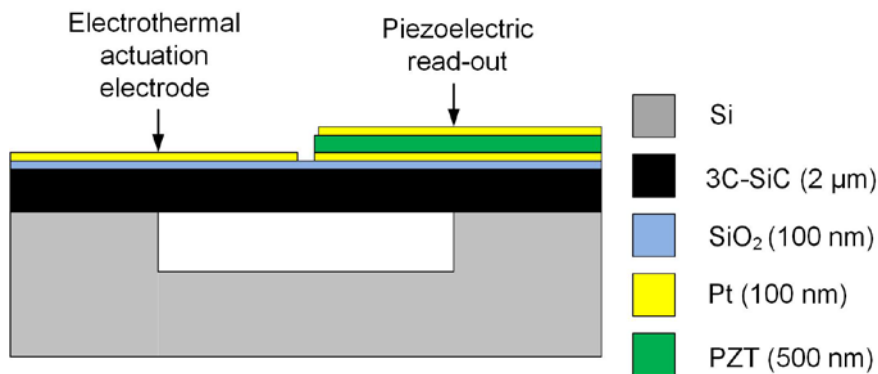


Figure 1: Side view schematic of SiC resonator with electrothermal actuation and piezoelectric read-out

For the cantilever device, the SiC structure has a length of 200 μm and a width of 100 μm . A 20 μm wide u-shaped Pt electrothermal actuation electrode has been positioned just off the anchor of the beam with the rest of the top surface utilized by a Pt/PZT/Pt piezoelectric sensor, as can be seen in the scanning electron microscope (SEM) image of Fig. 2a. The fabricated bridge resonator device can be seen in Fig. 2b, with a similar arrangement for actuation and sensing. The actuation electrode

has been placed at $L_b/3$, where L_b is the beam length, and the sensing electrode being on the opposite side of a 200 μm long bridge. Finally, an optical image of a ring resonator with a radius of 200 μm is shown in Fig. 2c. The electrothermal actuation electrode design is the same for the cantilever, bridge and ring (u-shaped design), while the Pt/PZT/Pt output port has been designed to maximize sensitivity by covering a larger area of the resonator.

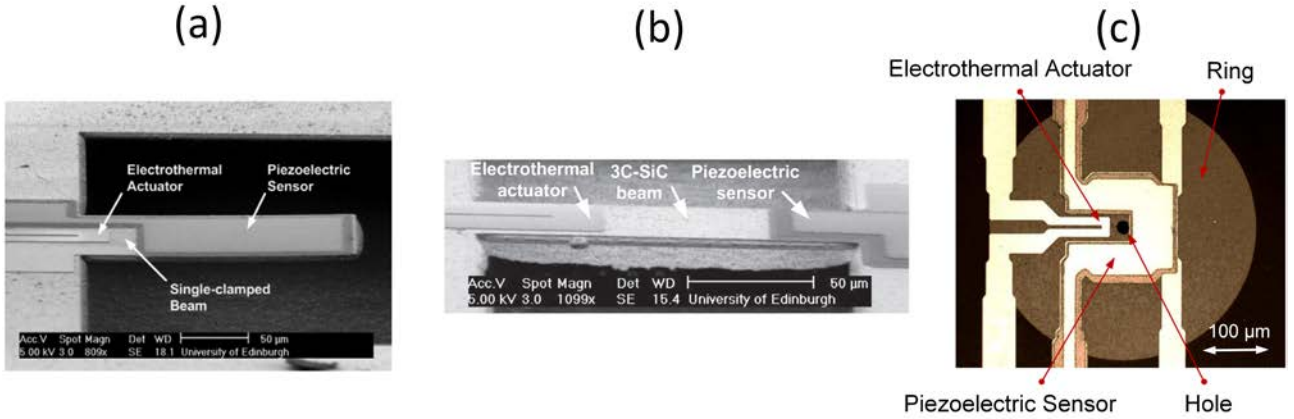


Figure 2: SEM and optical images of (a) cantilever [8], (b) bridge [10] and (c) ring [11] SiC MEMS resonators

The three devices have been characterized electrically using a DC supply for the input bias voltage and an HP8753C vector network analyzer, which supplied the AC actuation signal and measured the transmission frequency response from the piezoelectric output port.

Results and Discussion

All the devices reported here have been actuated with an AC input power of 10 dBm and a DC bias of at least between 0 V and 6 V. The cantilever, bridge and ring devices exhibit measured resonant frequencies of 522 kHz, 850 kHz and 497 kHz, respectively. As reported previously [5], it is expected that, for similar dimensions, the resonant frequency of a cantilever will be lower than a bridge, which has been confirmed in this work. The larger dimension (400 μm diameter) as well as the electrode configuration in the ring compared to the cantilever (200 μm length) may have contributed to the relatively similar resonant frequencies measured. The measurements have been performed at atmospheric pressure in air and the quality (Q) factors ranged from 70 to 410.

The response of the resonant frequency shift of the cantilever to the DC bias voltage applied to the Pt actuation electrode is shown in Fig. 3a, while a similar response for the bridge and ring resonators are also shown in Fig. 3b. It can be seen clearly that the DC tuning sensitivities of the ring and bridge resonators (between 58,000 ppm/V and 62,000 ppm/V and can reach up to 65,000ppm/V at 2V) are significantly higher than for the cantilever (240 ppm/V). The observed resonant frequency shift is probably a result of the thermal heat inducing stress on the resonator [13-15].

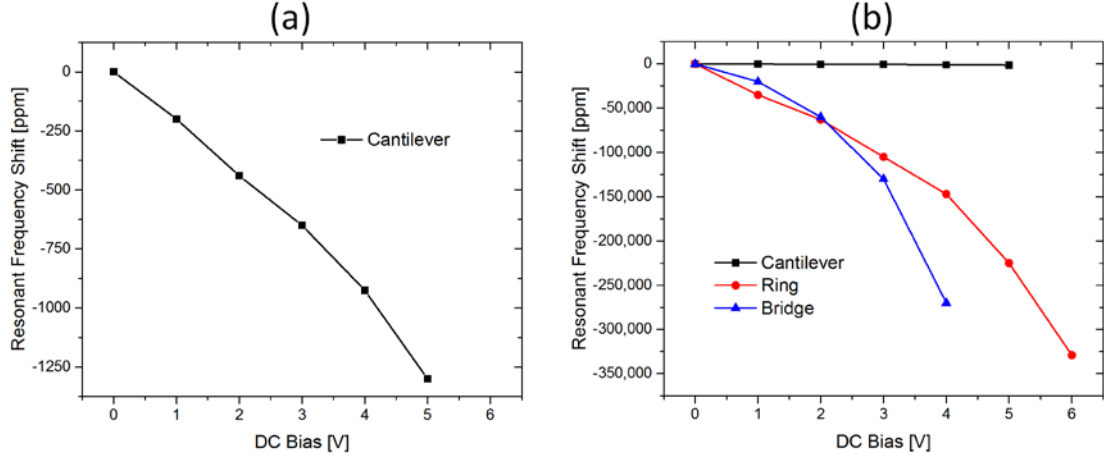


Figure 3: Measured shift in resonant frequency as a function of DC bias voltage for (a) cantilever and (b) cantilever, bridge and ring SiC resonators (see text for dimensions)

In order to confirm the influence of thermally induced stress on the resonant frequency shift of the resonators and to shed light on the difference in the measured tuning sensitivity between cantilevers and bridges/rings, FEM simulations have been performed to model the temperature increase and the stress change caused by the increase in DC bias voltage. Meshed models of the cantilever and bridge resonator designs have been created and simulated (since these two devices have the same length) for a DC tuning voltage up to 5 V, assuming a Young's modulus of 410 GPa for the SiC layer. Fig 4a shows the simulated temperature profile along the length of the cantilever and bridge for DC bias voltages ranging from 1 V to 5 V. It can be seen that the temperature increases as a function of DC bias, similar to work reported previously [5]. The simulations show that the electrodes induce the maximum temperature at the termination of the u-shape, which is 20 μm from the anchor for the cantilever and 67 μm from the anchor for the bridge, and that the value of the maximum induced temperature is higher for the bridge device. The temperature distribution along the beams shows significant differences between the cantilever and the bridge.

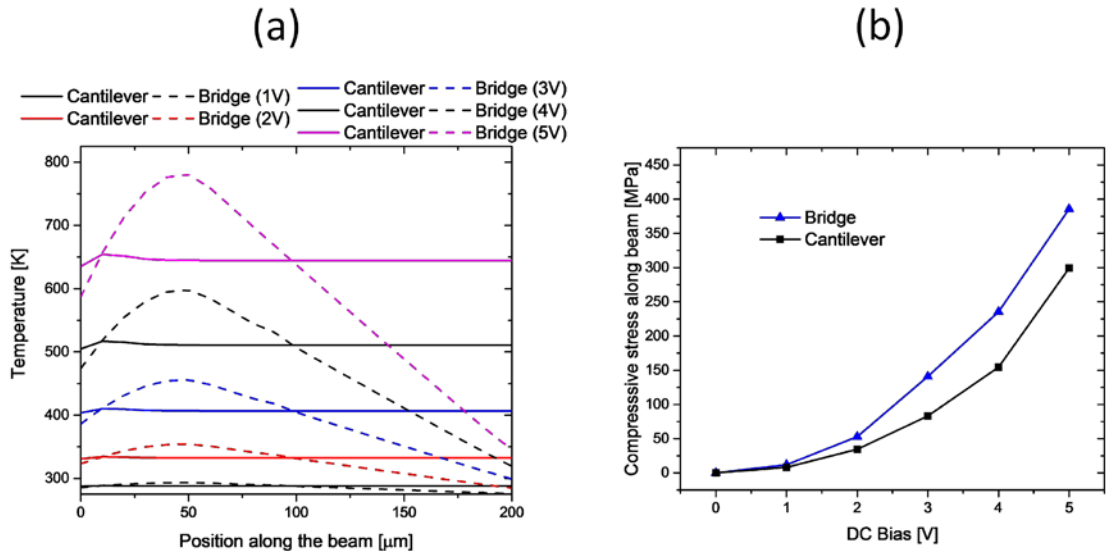


Figure 4: FEM simulated (a) temperature along the beam for DC bias voltages 1 V to 5 V (b) compressive stress in the SiC layer of the resonators as a function of DC bias voltage

Fig. 4b shows the simulated compressive stress of the SiC layer along the length of the beam for both the cantilever and the bridge designs. It can be seen that, for a given DC voltage increase, the stress is larger for the bridge resonator. It is likely that the higher compressive stress in the bridge is

a result of the higher maximum temperature and the difference in temperature distribution along the beam length (Fig. 4a), perhaps due to the location of the actuation electrode. The higher compressive stress may explain the larger resonant frequency shift measured in the bridge resonator (Fig. 3b). In addition, it is thought that a bridge could be more susceptible to an increase in thermally induced stress than a cantilever, because a bridge is clamped at both ends.

Conclusions

The tuning performance of SiC MEMS resonators consisting of cantilevers, bridges and rings actuated electrothermally and sensed piezoelectrically has been compared. Actuation has been performed using a u-shaped Pt electrode and read-out of the mechanical vibrations has been achieved by measuring the output voltage from a PZT layer. It has been found that the resonant frequencies of all three structures decrease as the DC voltage applied to the actuation electrodes has been increased. Moreover, the tuning sensitivity, measured in ppm/V, is about 250 times higher for a bridge or ring compared to a cantilever. FEM simulations have shown that, for a given increase in DC tuning voltage, the thermally induced stress in the SiC layer is larger for our bridge design than for the cantilever with the same dimensions. The frequency tuning capability of the devices that has been presented in this paper shows great promise for use in applications such as filters that require real-time adjustment of the mechanical resonance.

Acknowledgments

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